Accepted for publication in ApJ Letters
Preprint typeset using LaTeX style emulateapj v. 10/09/06

DISENTANGLING THE HERCULES STREAM[1]

T. Bensby,[2] M.S. Oey,[2] S. Feltzing,[3] and B. Gustafsson[4]

Accepted for publication in ApJ Letters

ABSTRACT

Using high-resolution spectra of nearby F and G dwarf stars, we have investigated the detailed abundance and age structure of the Hercules stream. We find that the stars in the stream have a wide range of stellar ages, metallicities, and element abundances. By comparing to existing samples of stars in the solar neighbourhood with kinematics typical of the Galactic thin and thick disks we find that the properties of the Hercules stream distinctly separate into the abundance and age trends of the two disks. Hence, we find it unlikely that the Hercules stream is a unique Galactic stellar population, but rather a mixture of thin and thick disk stars. This points toward a dynamical origin for the Hercules stream, probably caused by the Galactic bar.

Subject headings: Galaxy: disk — Galaxy: formation — Galaxy: evolution — solar neighbourhood — stars: abundances — stars: kinematics

1. INTRODUCTION

The stellar velocity distribution in the solar neighbourhood is manifoldly structured (see, e.g., Dehnen 1998; Skuljan et al. 1999; Famaey et al. 2005; Helmi et al. 2006; Arifyanto & Fuchs 2006). Prominent features are the Pleiades-Hyades super-cluster, the Sirius cluster, and the Hercules stream (also known as the u-anomaly). From a large sample of nearby G and K giants Famaey et al. (2005) found that the Hercules stream makes up approximately 6 % of the stars in the solar neighbourhood, and that they have a net drift of $\sim 40\ \mathrm{km\,s^{-1}}$ directed radially away from the Galactic centre. Just as for the Galactic thick disk, their orbital velocities around the Galaxy lag behind the local standard of rest (LSR) by $\sim 50\ \mathrm{km\,s^{-1}}$ (see also Ecuvillon et al. 2006 who found similar properties for the Hercules stream using nearby F and G dwarf stars).

Numerical simulations have shown that the excess of stars at $(U_{\rm LSR}, V_{\rm LSR}) \approx (-40, -50)\ \mathrm{km\,s^{-1}}$ can be explained as a signature of the Galactic bar (e.g., Raboud et al. 1998; Dehnen 1999, 2000; Fux 2001). If it is a chaotic process, where stars gets gravitaionally scattered from the inner Galactic regions by the bar, or if they are coupled to the outer Lindblad resonance of the bar is, however, uncertain (Fux 2001). Either way, this points to an origin for the Hercules stream that is related to the inner disk regions. So, is the Hercules stream a distinct stellar population with a unique origin and evolutionary history, or is it a mixture of different populations?

Using available data in the literature Soubiran & Girard (2005) found that most Hercules stars tend to follow the thin disk abundance trends. They, however, concluded that the existing knowledge about the chemical properties of the Hercules stream did not admit safe conclusions about the origin of the stream. We note that the distinct and well separated chemical signatures that the two disks exhibit (Fuhrmann 2004; Bensby et al. 2003, 2004b, 2005; Mishenina et al. 2004; Feltzing et al. 2007) are less separated in the abundance plots in Soubiran & Girard (2005) (compare, e.g., the abundance trends for oxygen in their Fig. 10 with Fig. 10 in Bensby et al. 2004b). This is likely an effect of merging different data sets, each containg different systematic errors.

To further study the origin of the Hercules stream we have observed a sample of 60 F and G dwarf stars, all kinematically selected to be members of the stream. By performing a strictly differential detailed abundance analysis of the Hercules stream stars relative to stars of the two disk populations previously studied by us (Bensby et al. 2003, 2005) we minimise uncertainties due to systematic errors in the analysis.

In this letter we focus on two elements that show distinct abundance trends for the thin and thick disks: Mg (e.g., Fuhrmann 2004; Feltzing et al. 2003; Bensby et al. 2003, 2005) and Ba (e.g., Mashonkina et al. 2003; Bensby et al. 2005). Other α-elements, iron peak elements, and r- and s-process elements will be presented in an upcoming paper (Bensby et al. 2007, in prep.), wherein we also will describe the observations, data reductions, abundance analysis, etc. (see, however, Bensby et al. 2006, where the results for a few other elements are briefly presented).

2. IDENTIFICATION OF HERCULES STREAM STARS

We used the kinematical method from Bensby et al. (2003, 2005) to define a sample of Hercules stream stars. This method assumes that a stellar population has a Gaussian velocity distribution and constitutes a certain fraction of the stars in the solar neighbourhood. Assuming that the solar neighbourhood is a sole mixture of the thin disk, the thick disk, the Hercules stream, and the halo, it is then possible to calculate the probabilities for individual stars (with known space velocities) to belong to either of the populations. We selected Hercules stream stars as those stars that have probabilities of belonging

[1] Based on observations collected with the MIKE spectrograph on the 6.5 m Magellan/Clay telescope at the Las Campanas observatory in Chile

[2] Department of Astronomy, University of Michigan, 830 Dennison Building, 500 Church Street, Ann Arbor, MI 48109-1042, USA; tbensby@umich.edu, msoey@umich.edu
[3] Lund Observatory, Box 43, SE-221 00 Lund, Sweden; sofia@astro.lu.se
[4] Department of Astronomy and Space Physics, University of Uppsala, Box 515, SE-751 20 Uppsala, Sweden; bg@astro.uu.se

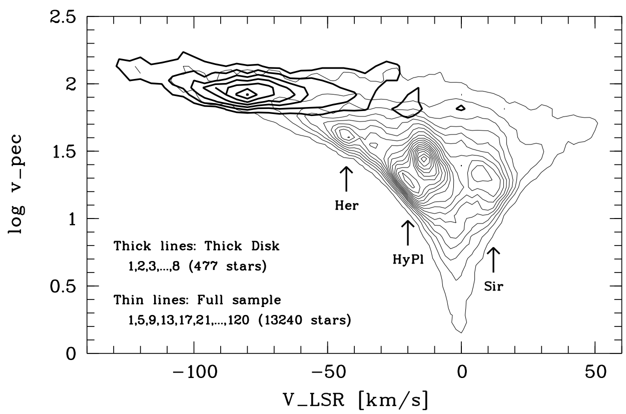

FIG. 1.— Velocity distribution of the F and G dwarf stars in the Nordström et al. (2004) catalogue (where $v_{\rm pec} \equiv (U^2_{\rm LSR} + V^2_{\rm LSR} + W^2_{\rm LSR})^{1/2}$). The Hercules stream (Her), the Hyades-Pleiades cluster (HyPl), and the Sirius group (Si) have been marked. Distances between the isodensity curves are also given in the plot.

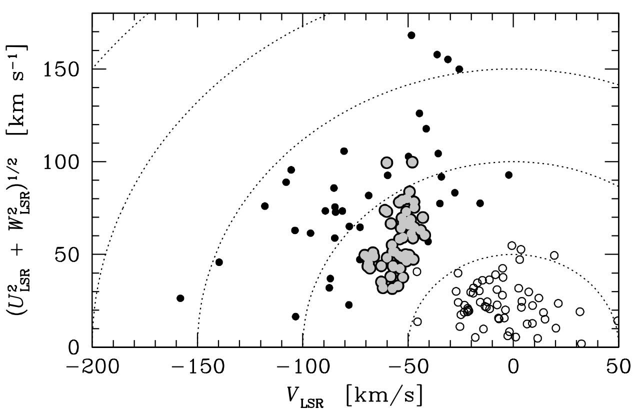

FIG. 2.— Toomre diagram for the Hercules stream sample (larger gray circles). Thin and thick disk stars from Bensby et al. (2003, 2005) are marked by open and black smaller circles, respectively.

to the Hercules stream that are at least as large as twice the probabilities of belonging to any of the other populations.

The Nordström et al. (2004) catalogue contains kinematic information for 13240 F and G dwarf stars in the solar neighbourhood. Considering the full catalogue we are able to kinematically tag 12040 stars as likely thin disk members, 438 as likely thick disk members, and 112 as likely Hercules stream members. Fig. 1 shows a contour plot of the distribution for all stars in the catalogue (thin solid lines), and density contours for the thick disk (thick solid lines).

The 60 Hercules stream stars in this study are shown in a Toomre diagram in Fig. 2 together with the 102 thin and thick disk stars from Bensby et al. (2003, 2005). Our Hercules stream sample is well confined and forms a distinct kinematical group. None of the thin and thick disk stars in Bensby et al. (2003, 2005) can be classified as Hercules stream stars.

3. BRIEF SUMMARY OF OBSERVATIONS, ABUNDANCE ANALYSIS, AND AGE DETERMINATIONS

High-resolution ($R \approx 65\,000$), high-quality ($S/N \gtrsim 250$) echelle spectra were obtained for 60 F and G dwarfs by TB in Jan, Apr, and Aug in 2006 with the MIKE spectrograph (Bernstein et al. 2003) on the Magellan Clay 6.5 m telescope at the Las Campanas Observatory in Chile. Solar spectra were obtained during the runs by observing the asteroid Vesta (in Jan), the Jovian moon Ganymede (in Apr), and the asteroid Ceres (in Aug).

For the abundance analysis we used the Uppsala MARCS stellar model atmospheres (Gustafsson et al. 1975; Edvardsson et al. 1993; Asplund et al. 1997). The chemical compositions of the models were scaled with metallicity relative to the standard solar abundances as given in Asplund et al. (2005), but with α-element enhancements[5] for stars with [Fe/H] < 0. To determine the effective temperature and the microturbulence parameter we required all Fe I lines to yield the same abundance independent of lower excitation potential and line strength, respectively. To determine the surface gravities we utilised that our stars have accurate Hipparcos parallaxes (ESA 1997). Final abundances were normalised on a line-by-line basis with our solar values as reference and then averaged for each element.

Stellar ages were determined from the Yonsei-Yale ($\rm Y^2$) α-enhanced isocrones (Kim et al. 2002; Demarque et al. 2004) in the $T_{\rm eff}$-$M_{\rm V}$ plane. Upper and lower limits on the ages were estimated from the error bars due to an uncertainty of ± 70 K in $T_{\rm eff}$ and the uncertainty in $M_{\rm V}$ due to the error in the parallax (see Bensby et al. 2003).

4. RESULTS AND DISCUSSION

Our abundance results are shown in Figs. 3a-d. While the [Mg/Fe] vs. [Fe/H] trends for the thin and thick disks are clearly separated they do merge as [Fe/H] ≈ 0 is reached. The [Ba/Fe] vs. [Fe/H] trend, on the other hand, keeps the two disks well separated until [Fe/H] ≈ 0.1. The separation between the thin and thick disks is larger when Mg is used as the reference element.

The observed thick disk [Mg/Fe] vs. [Fe/H] trend is due to the different production sites of Mg and Fe in SN II and SN Ia, respectively, operating at different time scales (see, e.g., McWilliam 1997).

The solar system abundance of Ba has been built up by two different production mechanisms that work on different timescales; the r-process which dominated at low metallicities ([Fe/H] $\lesssim -1.5$) and contributed $\sim 20\,\%$, and the s-process that dominated at higher metallicities and contributed $\sim 80\,\%$ (Travaglio et al. 1999). The increase (or the "bump") that can be seen in the [Ba/Fe]-[Fe/H] trend for the thin disk is likely to be a signature of when the s-process enrichment from AGB stars became significant (Travaglio et al. 1999). For other environments the mixture may be different, compare e.g. the Ba and Eu trends in Mashonkina et al. (2003). For the thick disk, the flat [Ba/Fe] trend could indicate that the s-process did not play a significant rôle in the Ba enrichment of the gas from which the thick disk formed (and hence the lack of the "bump").

4.1. *Abundance bimodality?*

A first impression is that most Hercules stream stars follow the trends as outlined by the thick disk. In the [Ba/Fe] vs. [Fe/H] plot this is especially evident and

[5] The α-element enhancement increases linearly from $[\alpha/\rm Fe] = 0$ at [Fe/H] $= 0$ up to $[\alpha/\rm Fe] = 0.4$ at [Fe/H] $= -1$, and is then constant $[\alpha/\rm Fe] = 0.4$ for lower metallicities.

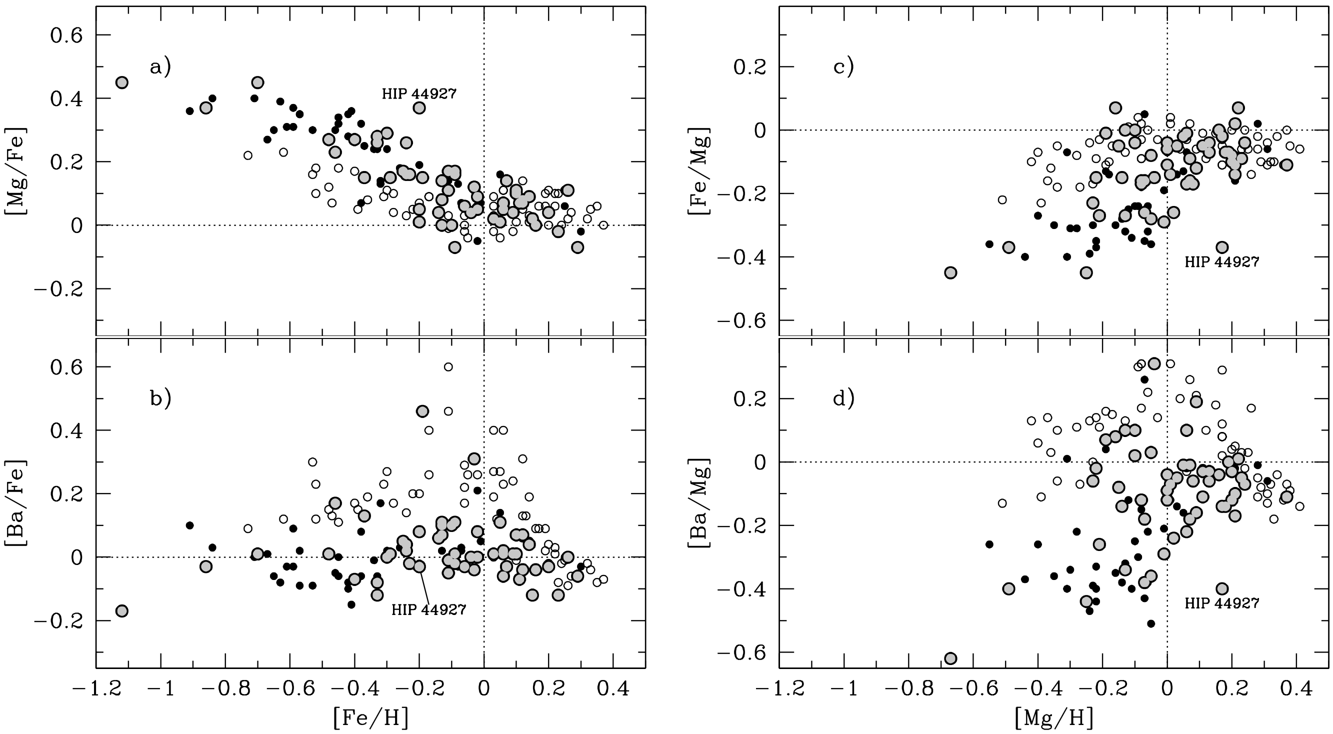

FIG. 3.— [Mg/Fe] and [Ba/Fe] vs. [Fe/H] (panels to the left) and [Fe/Mg] - [Mg/H] and [Ba/Mg] vs. [Mg/H] (panels to the right). Hercules stars are marked by larger gray circles. The thin and thick disk stars from Bensby et al. (2003, 2005) are marked by open and black smaller circles, respectively.

even up to metallicities as high as [Fe/H] $\approx +0.1$. In the [Mg/Fe] vs. [Fe/H] plot the Hercules stars follow the thick disk trend up to [Fe/H] ≈ -0.2 and may then show signs of a mixing between the two disks for higher metallicities. The [Fe/Mg] and [Ba/Mg] trends with [Mg/H] give similar results.

Apart from one star, HIP 44927, we do not find any Hercules stream stars that deviate from the thin and thick disk abundance trends. Recent observations have shown that bulge stars have large α-enhancements at solar and super-solar metallicities (Fulbright et al. 2006; Zoccali et al. 2006). This compares very well with what we see for HIP 44927, indicating that we might have picked up a bulge star in our Hercules sample. Its age $3.8^{+0.7}_{-0.4}$ Gyr is, however, inconsistent with the bulge being an old population. But there are indications that the bulge could contain stars as young as a few hundred million years (Gilmore 2003).

4.2. *Age bimodality?*

In Fig. 4 we plot stellar ages versus [Fe/H]. At metallicities below [Fe/H] = 0 it appears that the Hercules stream divides into two (or maybe three) branches: one that follows the thick disk age trend (the downward age-metallicity relation we see for the thick disk trend was seen in Bensby et al. 2004a and then verified by Haywood 2006 and Schuster et al. 2006); one that follows the thin disk age trend; and a few stars (4-5) that tend to have high ages of ~ 15 Gyr in the interval $-0.4 \lesssim$ [Fe/H] $\lesssim 0$. Once again, we see that the stars of the Hercules stream follow the trends outlined by the stars with kinematics typical of the thin and thick disks. As the uncertainties in the age determinations are notoriously difficult to estimate (see e.g. Jørgensen & Lindegren 2005), and generally come out too small when using standard methods

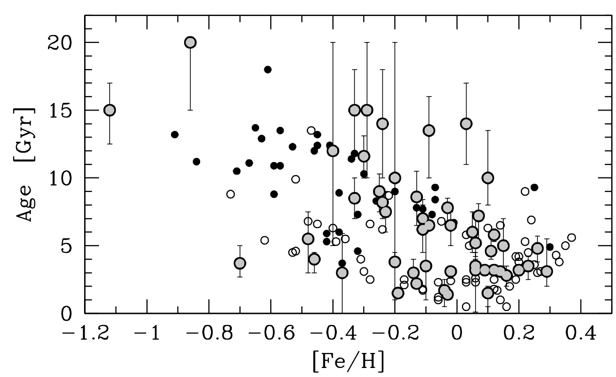

FIG. 4.— Ages vs. [Fe/H] for the Hercules stream stars (larger gray circles). Thin and thick disk stars from Bensby et al. (2003, 2005) are marked by open and black smaller circles, respectively. Error bars show the upper and lower age estimates due to the uncertainties in the $T_{\rm eff}$s and in the distances to the stars.

one should be careful to make far fetched interpretations about the few outliers.

4.3. *The origin of the Hercules stream*

Some Galactic streams may have origins due to minor mergers (e.g. Navarro et al. 2004). Could this be the case for the Hercules stream? Such a merging system must then have had chemical properties similar to the present Galactic disks. Thus, such a merging galaxy must have had chemical properties that depart considerably from those of local dwarf galaxies (cf., e.g. Venn et al. 2004) and would presumably be more similar to a major spiral galaxy. There is no observational evidence that such a substantial merger occured in the Milky Way during the last 10 Gyr (Gilmore et al. 2002). Instead, our results strongly suggest that the Hercules stream has a dynamical origin, presumably due to the dynamical effects of the Galactic bar, and it may consist of stars from the inner Galactic disks.

Are we then tracing the inner thin disk or the inner thick disk? As no detailed abundance data for the inner disks have been obtained yet, only indirect evidence is available. The thick disk velocity dispersion is about twice that of the thin disk, but its rotational velocity is just $\sim 80\,\%$ of that of the thin disk. According to the Toomre stability criterion ($Q \propto V_{\rm rot} \cdot \sigma_{\rm R}$; Toomre 1964) the thick disk should be slightly more stable than the thin disk ($Q_{\rm thick\,disk} \approx 1.6 \cdot Q_{\rm thin\,disk}$) and less disturbed by gravitational influences from the Galactic bar. Since the inner thin disk is thought to have more evolved stellar populations, as judged from its abundance and age gradients, the higher ages and [α/Fe] ratios of the Hercules stream seem consistent with an inner thin disk origin. On the other hand, the abundance patterns are better matched to the thick disk in general, and it is plausible that the thick disk also has a metallicity gradient, which would then match the relative number of high-metallicity stars in the stream.

As the stars of the Hercules stream display the distinct abundance and age trends of *both* the thin and thick disk stars, it is likely that it actually is a mixture of the two disks. This is also suggested by the Toomre stability criterion being similar for the two disk components. A preliminary investigation of the relationship between the ages and abundance ratios for our stars in the Hercules stream shows that they are correlated in a way expected for an Hercules stream composed of Galactic disk stars (see further Bensby et al. 2007, in prep.)

5. CONCLUSION

The Hercules stream is unique in the sense that it forms a well defined enhancement in the velocity distribution of nearby stars. However, large ranges in stellar ages and elemental abundances indicate that it is not a distinct stellar population. Instead, as the age and abundance trends in the Hercules stream are similar to the trends in the thin and thick disks, we conclude that the Hercules stream is a mixture of thin and thick disk stars. This result is in concordance with models that suggest that the kinematical properties of the Hercules stream are coupled to dynamical interactions with the Galactic bar. Whether the Hercules stream stars have a real inner disk origin or whether they are nearby stars whose kinematics are an effect of the outer Lindlad resonance of the bar, which may be situated near the solar neighbourhood (Dehnen 2000), is unclear. Further insights into this problem could be gained by making comparisons to detailed abundance data from the *in situ* inner Galactic thin and thick disks. As such data currently are unavailable, we have initiated a study to obtain them.

This work was supported by the National Science Foundation, grant AST-0448900, and a grant from the Swedish Research Council. SF is a Royal Swedish Academy of Sciences Research Fellow supported by a grant from the Knut and Alice Wallenberg Foundation.

REFERENCES

Arifyanto, M. I., & Fuchs, B. 2006, A&A, 449, 533
Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASP Conf. Ser. 336: Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, 25
Asplund, M., Gustafsson, B., Kiselman, D., & Eriksson, K. 1997, A&A, 318, 521
Bensby, T., Feltzing, S., & Lundström, I. 2003, A&A, 410, 527
—. 2004a, A&A, 421, 969
—. 2004b, A&A, 415, 155
Bensby, T., Feltzing, S., Lundström, I., & Ilyin, I. 2005, A&A, 433, 185
Bensby, T., Oey, M. S., Feltzing, S., & Gustafsson, B. 2006, in The Metal Rich Universe, Las Cancajos, La Palma, Spain, 12-16 June, 2006, Garik Israelian and Georges Meynet (eds), Cambridge University Press, in press, (astro–ph/0610754)
Bernstein, R., Shectman, S. A., Gunnels, S. M., Mochnacki, S., & Athey, A. E. 2003, in Proceedings of the SPIE, Volume 4841, ed. M. Iye & A. F. M. Moorwood, 1694–1704
Dehnen, W. 1998, AJ, 115, 2384
—. 1999, ApJ, 524, L35
—. 2000, AJ, 119, 800
Demarque, P., Woo, J.-H., Kim, Y.-C., & Yi, S. K. 2004, ApJS, 155, 667
Ecuvillon, A., Israelian, G., Pont, F., Santos, N. C., & Mayor, M. 2006, A&A, accepted, (astro-ph/0608669)
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101
ESA. 1997, The HIPPARCOS and TYCHO catalogues, ESA SP Series vol no: 1200, Noordwijk, Netherlands
Famaey, B., Jorissen, A., Luri, X., Mayor, M., Udry, S., Dejonghe, H., & Turon, C. 2005, A&A, 430, 165
Feltzing, S., Bensby, T., & Lundström, I. 2003, A&A, 397, L1
Feltzing, S., Fohlman, M., & Bensby, T. 2007, A&A accepted
Fuhrmann, K. 2004, Astronomische Nachrichten, 325, 3
Fulbright, J. P., McWilliam, A., & Rich, R. M. 2006, AJ, submitted, (astro-ph/0609087)
Fux, R. 2001, A&A, 373, 511
Gilmore, G., Wyse, R.F.G., & Norris, J.E. 2002, ApJ, 574, L39
Gilmore, G. 2003, in Revista Mexicana de Astronomia y Astrofisica Conference Series, ed. V. Avila-Reese, C. Firmani, C. S. Frenk, & C. Allen, 149–157
Gustafsson, B., Bell, R. A., Eriksson, K., & Nordlund, A. 1975, A&A, 42, 407
Haywood, M. 2006, MNRAS, 371, 1760
Helmi, A., Navarro, J. F., Nordström, B., Holmberg, J., Abadi, M. G., & Steinmetz, M. 2006, MNRAS, 365, 1309
Jørgensen, B. R., & Lindegren, L. 2005, A&A, 436, 127
Kim, Y., Demarque, P., Yi, S. K., & Alexander, D. R. 2002, ApJS, 143, 499
Mashonkina, L., Gehren, T., Travaglio, C., & Borkova, T. 2003, A&A, 397, 275
McWilliam, A. 1997, ARA&A, 35, 503
Mishenina, T. V., Soubiran, C., Kovtyukh, V. V., & Korotin, S. A. 2004, A&A, 418, 551
Navarro, J. F., Helmi, A., & Freeman, K. C. 2004, ApJ, 601, L43
Nordström, B., Mayor, M., Andersen, J., Holmberg, J., Pont, F., Jørgensen, B. R., Olsen, E. H., Udry, S., & Mowlavi, N. 2004, A&A, 418, 989
Raboud, D., Grenon, M., Martinet, L., Fux, R., & Udry, S. 1998, A&A, 335, L61
Schuster, W. J., Moitinho, A., Márquez, A., Parrao, L., & Covarrubias, E. 2006, A&A, 445, 939
Skuljan, J., Hearnshaw, J. B., & Cottrell, P. L. 1999, MNRAS, 308, 731
Soubiran, C., & Girard, P. 2005, A&A, 438, 139
Toomre, A. 1964, ApJ, 139, 1217
Travaglio, C., Galli, D., Gallino, R., Busso, M., Ferrini, F., & Straniero, O. 1999, ApJ, 521, 691
Venn, K. A., Irwin, M., Shetrone, M. D., Tout, C. A., Hill, V., & Tolstoy, E. 2004, AJ, 128, 1177
Zoccali, M., Lecureur, A., Barbuy, B., Hill, V., Renzini, A., Minniti, D., Momany, Y., Gomez, A., & Ortolani, S. 2006, A&A, 457, L1